INERTIA OF LOUDNESS MEASUREMENT IN RELATION TO SOUND LEVEL

H. Niese

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16. Abstract In order to simulate the properties of the ear for objective loudness-level meters, the ear is viewed as a closed inertial system with a time constant of 23 msec for acoustic power. This figure was determined through subjective loudness-comparison experiments. Two alternating short tones of different durations (ratio 1:2) were compared, and the loudness of one adjusted until it equalled that of the other. No dependence of the loudness rise on loudness level was ascertained. Two electrical circuits for appropriately designed loudness-level meters are described.

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H. Niese
Institute for Electrical and Architectural Acoustics,
Dresden Engineering College

1. Introduction

In designing objective loudness level meters, the inertia given to the indicator system is of great importance. In order that even brief noises or noise forms, composed of periodically recurring, brief, single pulses, furnish readings consistent with what is heard, the inertia of the measuring apparatus must be modeled on the inertia of the sense of hearing.

A short sound pulse with certain physical parameters of duration and amplitude generates a certain sensation of loudness. It has been known for a long time that the perceived loudness produced by a sound pulse of constant amplitude depends on the duration of the pulse. This effect can be attributed to the evident inertia of the sense of hearing. An electrical measuring system without inertia would always register the peak value, independently of the duration of the sound pulse. However, if the system has a very great inertia, the final reading would be attained only for relatively protracted sounds, while short sound pulses would not set the system in motion at all, and thus would not produce any reading. Inasmuch as the short sound event was audible, and thus had a certain loudness level, a measuring device is expected to indicate this loudness level in agreement with the subjective perception. This problem is important in loudness measurements not only for single, brief sound events, but in fact for all noise forms which have a time-varying envelope curve. In particular, this includes all noises containing acoustic pressure peaks, either periodically repeated or statistically

*Numbers in the margin indicate pagination in the foreign text.

distributed. Such noises are very common in practical loudness level measurements, and are produced wherever machine parts are moving rhythmically, such as in internal-combustion engines, compressed air hammers, typewriters, punches, etc.

The importance of this group of problems is known to every acoustic engineer. There are different views only on the magnitude of the inertia to be incorporated in the electrical measuring system. For instance, DIN [Deutsche Industrie-Norm; German Industrial Standard] provisions [2] specify that the reading shall have a certain inertial property in the standard German loudness level meter (the DIN loudness level meter), a property based on the studies of v. Bekesy [1]. Namely, a sound pulse of a certain duration must deliver a certain fraction of the final deflection produced by a steady tone of the same amplitude. Recently, well-founded doubts have been raised about the correctness of this requirement, since it has been repeatedly found that the readings obtained with this device from "peak-containing" noises were too small in comparison with the subjective judgement. Quietzsch [3] and Niese [4], by having a large number of subjects judge a series of practical noises as to loudness, were able to show that the DIN loudness level meter gave readings which were too small by up to 20 phon and more when compared with mean subjective judgements. Obviously, the inertia chosen for this device is too large. As a result of this experience, a number of acoustic engineers have abandoned "inertial" sound intensity meters, and employed pure peak-value meters, because they provide "more accurate" readings. Using pure peak-acoustic-pressure meters certainly does not solve the problem. A simple experiment immediately shows that, apart from the peak acoustic pressure, the duration of a sound pulse also influences the sound intensity. If one listens to single sound pulses of constant amplitude of steadily decreasing duration, a marked decrease in loudness is

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noted. This observation shows that there is nevertheless a clear inertial effect in the hearing mechanism.

In using this inertial property as a model for loudnessulevely meters, the acoustic engineer does not care where the inertial property acts in the ear, or what its components are. He views the hearing organ as a closed system with the prevailing physical acoustic pressure as input and the subjective perceived loudness as output. The relationship between input and output can be discovered through appropriately chosen subjective loudness studies. For instance, by comparing sound intensities of short tones, Niese [5] found a time constant of about 23 msec for acoustic power, which describes the inertial property of the hearing sensation in good approximation. The value of 23 msec for the time constant of the inertial system transmitting the sound signals characterizes a lesser inertia than required in the DIN loudness level meter, so that incorporating this inertial property in loudness level meters can be expected to yield readings in better agreement with subjective judgements. Niese has carried out studies on this point with defined noise forms with a time-varying envelope for the time function, such as sinusoidally, rectangularly, and pulse-modulated tones [6].and noises with a primary tone and superimposed pulses [7]; these studies have shown that good agreement with subjective judgements of loudness can be achieved with this inertial property. Good results were also obtained from measurements of a large number of practical noises [4] with a loudness level meter designed on this principle and from simultaneous subjective loudness judgements.

Since measurements of the inertia of hearing and studies on the fitness of the inertial representation have always been con-ducted with easily comparable, mean acoustic pressure levels between 60 and 80 dB, there arises the question of how the inertia

of hearing depends on this level. In order to fill this gap in knowledge for the region of practical interest, a number of measurements are described in this article, designed first to verify previous figures on this inertia, and second, to shed light on the level-dependence of the time constant of the ear.

2.   The Measuring Procedure

In order to determine the time constant of an inertial system, a step function is applied to the input of the system, and the resulting rise process is observed at the output terminals. From the form of the output as a function of time, the inertial property of the system can be determined. By analogy, the hearing organ is considered as a closed system, and the attempt is made to determine by experiment the form of the output resulting from a sudden stimulus at the input. In this case, the input stimulus is one of the physical parameters of the sound field, and the output is characterized by the perceived loudness. Unfortunately, it is not possible to fix the relationship between stimulus and sensation in the hearing organ, since no subject has the ability to make a definite statement on the form of the perceived loudness rise resulting from a sudden sound stimulus.

Bekesy [1] solved this problem by having his subjects listen to short tones of variable duration, and adjust the loudness of a steady tone until it was equal to that of the short tone of a particular duration. From the amplitude of the adjusted loudness of the steady tone, the loudness level of the short tone can be deduced, which provides one measured point for that specific duration of the short tone. Plotting the measurements against the duration furnishes a curve of loudness vs. time for a suddenly sounded tone.

Niese [5] attempted to repeat Bekesy's procedure. However, in the course of preliminary experiments, it was found that the

judgements were so scattered that he did not dare averaging them. Obviously, it is very difficult to compare the loudness of two tones of different durations. The short tone, presented as a click, produces a completely different type of sensation from that of the steady tone, so that the measurement becomes a purely subjective matter for the test subject. In many cases, the subjects were hesitant, and finally gave judgements which fluctuated widely when the measurements were repeated.

In order to free the measuring procedure from these inadequacies, Niese [5] employed a procedure in which the subjects had to adjust the loudness of two presented short tones until they were equal. The short tones were presented in alternation in a slow periodic sequence. One of the short tones was always of constant duration, and its intensity could be controlled by the subject. The other short tone was presented with constant intensity, and its duration was varied from one series of experi- /145 ments to the next. Measurements were taken with three different frequencies for the sinusoidal short tones. It was found that the measured values were independent of the frequency employed. The regularity of the loudness rise could be derived from the ratios of the intensities chosen by the subject to produce equal loudness. The resulting curve was best described when a time constant of 23 msec was employed for the inertial property of hearing, using acoustic intensity or acoustic power as the input quantity.

The inertia of hearing found in this way was smaller than that given previously by Bekesy [1]. Probably, with the prolonged comparison tones used by Bekesy, fatigue and adaptation of the ear played a role and thus led to other results.

In the experiments described here, an even more refined measurement method is utilized, in order to exclude any possible systematic errors in judgement and to further depress the scattering of the judgements. To prevent ear fatigue, sinusoidal short

tones were again selected for the subjective hearing comparison. The procedure of determining the rise function from the ratios of the adjusted short-tone intensities was also retained. There might still be systematic errors in judgement and relatively scattered judgements due to the variation in the ratio of the durations of the short tones presented. In order to eliminate this possible influence, the duration of the comparison short tone was varied in these measurements, and always selected so that in every series of experiments, the subject always had to compare a pair of short tones with a duration ratio of 1:2.[1]

It also appeared possible that loudness judgements could be systematically influenced by the different spectra resulting from the differing durations of the short tones, since Feldtkeller and Zwicker [8] have shown that the width of noise spectra exerts a substantial influence on the loudness perception. They fou that the entire audible frequency range could be divided up into 24 subregions of specific bandwidth, within which the perceived loudness is independent of the width of the spectrum. These spectral subregions develop within the hearing organ for the perception of loudness, and, within a narrow range, have variable central frequencies. Since no statement can yet be made

[1]An article published in the interim by E. Port (Frequenz, Vol. 13, No. 8, p. 242) shows that, in his measurements to determine the time constant of the ear, which were taken in a similar manner, the scattering of the measurements was greater when the durations of the tones to be compared were very different. On the other hand, the scattering of the measurements was also astonishingly small in his experiments when the durations were about equal. Obviously it is even simpler, as indicated by experience in subjective studies, to compare two short tones of roughly equal duration and equal frequency with each other, than to compare steady noises of very different frequency content. The measuring method employed here, by choosing a constant tone-duration ratio of 1:2, avoids the causes of inaccuracy established by Port in his studies. Nevertheless, the results obtained by Port agree with those presented in this report within the expected limits of accuracy, and can be viewed as confirmation.

on the formation time of the subregions determined for steady
excitations, and since the formation time may be related to the
inertia under investigation, the spectral widths employed for
the measurements with sinusoidal short tones were held almost
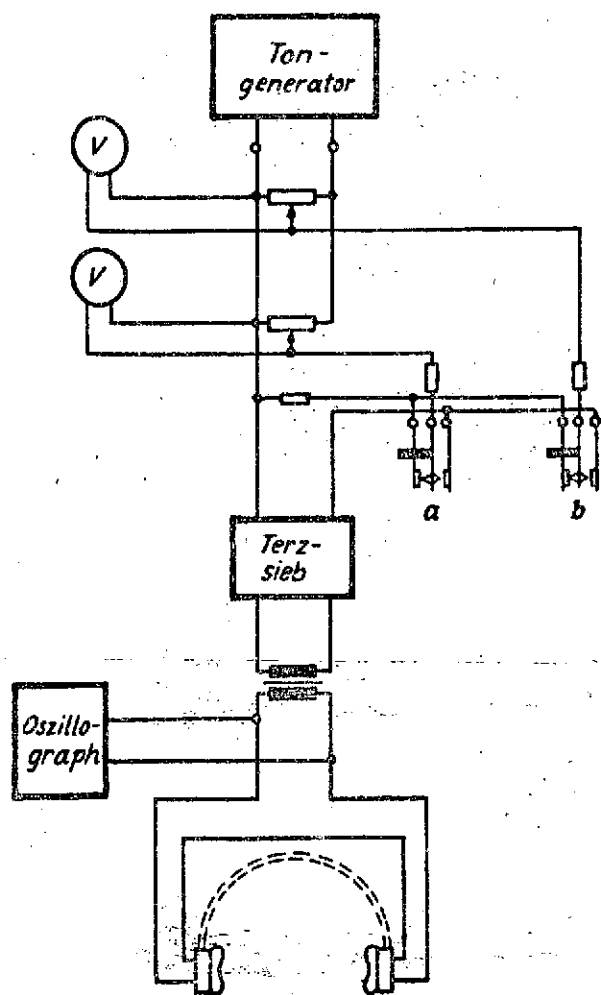entirely within the given subregions as a precaution.

Fig. 1. Block diagram of the
circuit for loudness-comparison
measurements.

Key: a. Tone generator
     b. Oscillograph
     c. One-third octave filter

Figure 1 shows a block
diagram of the measurement
apparatus. A tone generator
feeds two voltage dividers.
The setting of one of the
voltage dividers was fixed
by the person running the
experiment for each series of
measurements. The other
voltage divider was given to
the subject. The sinusoidal
short tones were generated
with the aid of a mechanical
control mechanism. At the
edge of a rotating disc driven
by a motor with controlled
rate of revolution, the con-
tact banks designated a and b
in Fig. 1 were situated. The
disc had replaceable cams of
various lengths, and as it
rotated, it actuated the con-
tacts, so that short tones in
the prescribed rhythm were fed
to the attached one-third
octave filter. For impedance
matching at the filter, there
was a subsequent transformer with the widest possible linear
frequency response, and this transformer in turn fed moving-coil

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headphones. The hooked-up oscillograph served to check the short tones generated.

Since it had been found in earlier measurements [5] that the inertia of the ear was virtually independent of the chosen frequency of the measuring tones, these studies to determine the level-dependence of hearing inertia were conducted only with /146 sinusoidal short tones of 1000 Hz frequency. The headphones employed were calibrated by subjective comparison with a plane wave, and voltages were applied which corresponded to loudness levels of 30, 50, 70, and 90 dB for the steady tone. In every revolution of the disc in the control mechanism, the contact bank a is actuated once and then, after a half revolution, the contact bank b. The rate of revolution of the disc is regulated so that there is a short tone after each 0.5 sec. The duration of contact at a and b can be chosen by exchanging the cam, always in the ratio of roughly 1:2. The short tones last for 200, 100, 50, 20, 10, and 5 msec in the various tests. The precise duration of contact is determined with the aid of a microchronometer; they deviate only slightly from the intended times. These deviations are taken into account in evaluating the measurements. Figure 2 shows a segment of the generated sequence of short tones. The contact times T_1 and T_2 were fixed for each series of experiments, and one of the two voltages u_1 or u_2 was also adjusted in line with the desired level. The magnitude of the other voltage could be varied by the subject.

To prevent any spectral influence on the measurements, the short tones were fed to the headphones through a one-third octave filter. This filter suppresses all oscillations resulting from the "on" and "off" switching process, and lying outside the one-third octave around the central frequency of 1000 Hz. This guaranteed that only a narrow frequency range would generate a response in the ear. Cutting off the high-frequency component
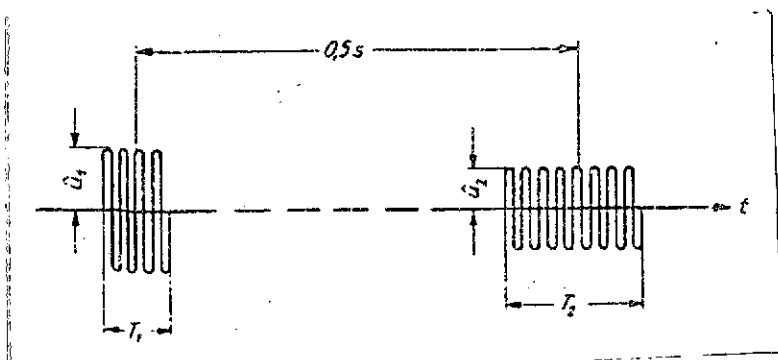
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Fig. 2. Schematic of a pair of short tones from the sequence presented for subjective loudness comparison.

$T = 10$ ms $T = 20$ ms
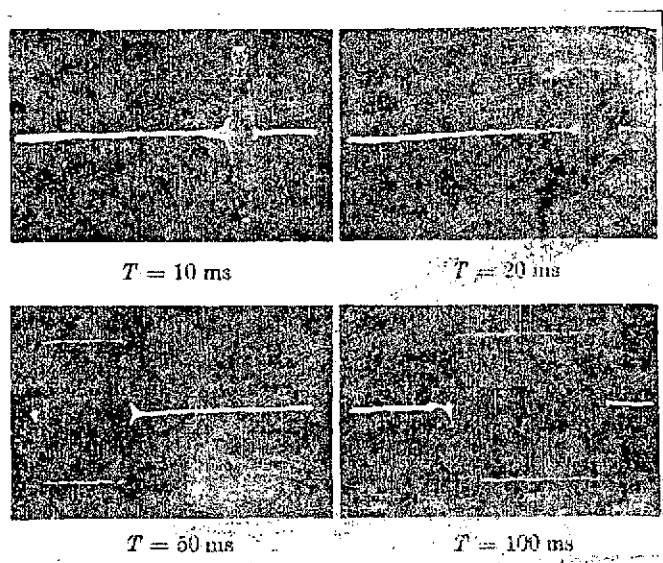
$T = 50$ ms $T = 100$ ms

Fig. 3. Oscillogram of the short tones with various tone durations for subjective loudness comparison.

inevitably brings about a rather "soft" switching process by smoothing out the sides of the voltage curves. Figure 3 shows oscillograms of some of the time functions of the short tones presented to the subjects. The smoothing of the "on" and "off" slopes can be clearly recognized; it extends over about three oscillations, independent of the duration of the short tone. Hence, the mean short-tone duration is preserved, due to the uniformity of the smoothing effect, although the overall process is somewhat stretched out. Since the shortest duration was about 5 msec, the short tone thus contained five complete 1000-Hz oscillations, and since the high switching frequencies were not transmitted to to the band limitation, the arbitrary switching-on phases of the short tones were inaudible, so that the same note was always produced.

Since, for short sound signals, the perceived loudness is directly related to the energy of the sound signal [5, 11], it is of particular interest to determine the energy loss experienced by the shortest tones due to the band limitation. The spectral power

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power density of the unfiltered short tone with the employed
duration of 5.8 msec was calculated and compared with that of the
filtered short tone. This comparison showed that only the low-
energy secondary maxima in the spectral representation were
suppressed by the filter, so that there is only a negligible
energy loss in the graphic integration of the two spectra. For
the longer short tones, this energy loss disappears completely
as the effective duration is increased.

For every series of tests, ten subjects participated suc-
cessively in the subjective measurements. To shield the subject
from any environmental influences, he was seated in a special room,
separated from the director of the experiment and the measuring
apparatus. Apart from the headphones, he was provided with only
a continuously variable control, which did not exhibit any clues
as to the control setting. The subject was told to first discover
which of the two short tones presented in alternation was con-
trollable, by setting the control to extreme positions, in order
then to adjust the control until the two short tones gave the same
impression of loudness. The participants in the experiments were
mostly assistants at the Institute and between 20 and 30 in age.
Since they had participated in similar loudness-comparison tests,
they could be considered experienced. Some other subjects were
also employed who had never taken part in hearing comparisons,
in order to see if they showed other inclinations in making the
equal-loudness adjustments. No differences in judgement were
ascertained from the results of measurements for these two groups.

In every series of tests, the short-tone durations were held
constant. Each subject made the equal-loudness adjustment for
the loudness levels 30, 50, 70, and 90 dB in succession. A sub-
jective effect was found, namely that the adjustable sound was
generally set higher. Because of this, in a second run, the
other short tone was made adjustable. This was achieved simply

by interchanging the feed lines (see Fig. 1) leading to the contact banks a and b. Thus, each subject delivered two verdicts for the same measurement, so that 20 judgements could be evaluated to establish one measured point. In order to obtain information about the mechanics of the ear, if possible, and perhaps to pinpoint the site of the inertial property, single-ear measurements were conducted at 50 dB. Loudness was compared in listening with first one ear and then the other. In addition, the controllable short tone was also interchanged in these single-ear measurements as well, so that 40 judgements were available to establish one measured point.

In each further series of measurements, the short tone durations were chosen differently, where the ratio of roughly 1:2 for the short tones to be compared was retained. The short tone durations 5-10 msec; 10-20 msec; 20-50 msec; 50-100 msec; and 100-200 msec were employed for the hearing comparisons. No times longer than 200 msec were employed because, according to the earlier measurements of Bekesy [1] as well, tones of such duration already give the same impression of loudness as steady tones of the same amplitude. In this case, since the repetition frequency was 1 Hz for the pair of tones, there was a 350-msec pause between the short tones. In the light of the rise process and from direct measurements of the decay process of the loudness perception made by Steudel [9], this recovery time for the ear appears sufficient, so that we did not have to fear that the perception of a short tone would be affected by the one preceding. The shortest duration of a tone was limited by the response time of the preceding one-third octave filter, and could be viewed as just barely tolerable at 5 msec. Thus, doubling the duration at each step gave six measurement points between 5 and 200 msec to characterize the rise in the loudness curve.
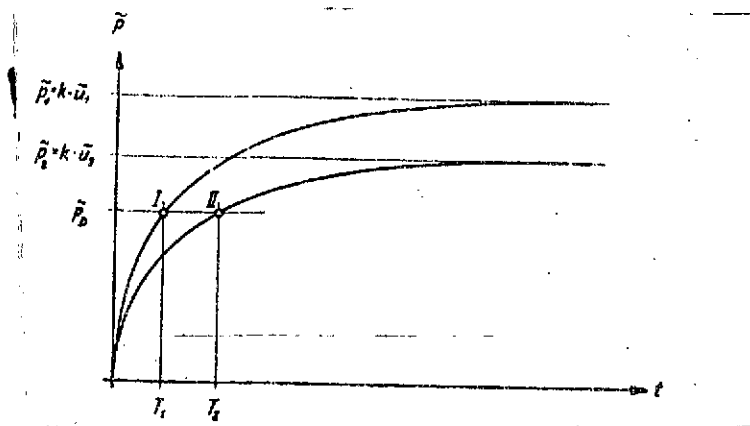
Fig. 4. Schematic of perceived loudness of short tones as a function of duration to illustrate the analysis of the experiment.

Figure 4 will illustrate the determination of the loudness-rise law from the voltage ratios furnished by the subjects to equate loudness for the short tones. The ordinate is the effective acoustic pressure, proportional to the measuring voltages. The horizontal axis is the time scale. The subjective loudness perception of the first tone (cf. Fig. 2) rises as the duration of the tone increases in accordance with some function $\phi(t)$, and after an infinitely long "on" time, reaches the limit given by the acoustic pressure $\tilde{p}_1 = \tilde{u}_1 \cdot k$. The subjective loudness rise of the second comparison short tone obeys a proportional rise law, if it can be assumed that small changes in level cause only small changes in the behavior of the rise. However, if the first tone lasts only until time T_1, a loudness is obtained at Point I which corresponds to the acoustic pressure $\tilde{p}_D$ of an associated steady tone. The second short tone, set to the same impression of loudness, and with the acoustic pressure $\tilde{p}_2 = \tilde{u}_2 \cdot k$ and the "on" time T_2 likewise corresponds at Point II to the loudness of the steady-tone acoustic pressure $\tilde{p}_D$. Thus we can equate the loudnesses of the steady tone of acoustic pressure $\tilde{p}_D$ and the short tones of acoustic pressures $\tilde{p}_1$ and $\tilde{p}_2$ and durations T_1 and T_2 respectively, so that the function $\phi(t)$ describing the rise must satisfy:

$$\tilde{p}_D = \tilde{p}_1 \, \varphi(T_1) = \tilde{p}_2 \, \varphi(T_2)$$

Since the acoustic pressures are proportional to the measurement voltages, we obtain the following equation for the ratio of the values of the rise function at two different points:

$$\varphi(T_1) = \frac{\tilde{u}_2}{\tilde{u}_1} \varphi(T_2)$$

For large values of T_2, at which we can assume that the full loudness impression corresponding to the acoustic pressure $\tilde{p}_2$ is produced, the function $\phi(t)$ acquires the value 1. The time 200 msec should be long enough, so that the first function point $\phi(T_1)$ is determined only by the ratio of the adjusted voltages. The next value of the function for $T_1/2$ is obtained from the adjusted voltage ratio when the durations T_1 and T_2 are halved, where now $\phi(T_2)$ in the determination equation must be set equal to the previously found value for $\phi(T_1)$, as a result of the halving of the durations. Continuing to halve the durations T_1 and T_2, we acquire a series of measurement points for the loudness-rise function $\phi(t)$, which, when multiplied by an acoustic pressure $\tilde{p}$, yields its effective loudness as a function of effective duration on the linear acoustic-pressure scale. Taking the logarithm of the rise law found for each of the four levels, and simultaneously normalizing with respect to the reference acoustic pressure $\tilde{p}_0 =$ = $2 \cdot 10^{-5}$ N/m^2 in accordance with the definition of loudness:

$$L = 20 \lg \frac{\tilde{p} \cdot \varphi(t)}{\tilde{p}_0},$$

we obtain the rise in perceived loudness as a function of the effective duration with the sound level for the steady tone as a parameter.

3. Results of the Measurements

The loudness judgements given by the subjects are treated by the previously described procedure and presented in several diagrams. Figure 5 shows the loudness level as a function of the effective duration of a 1000-Hz sinusoidal tone for acoustic levels of 30, 50, 70, and 90 dB for the sinusoidal tone. Each measurement point designated with a circle is the mean value calculated from 20 judgements by ten different subjects. The
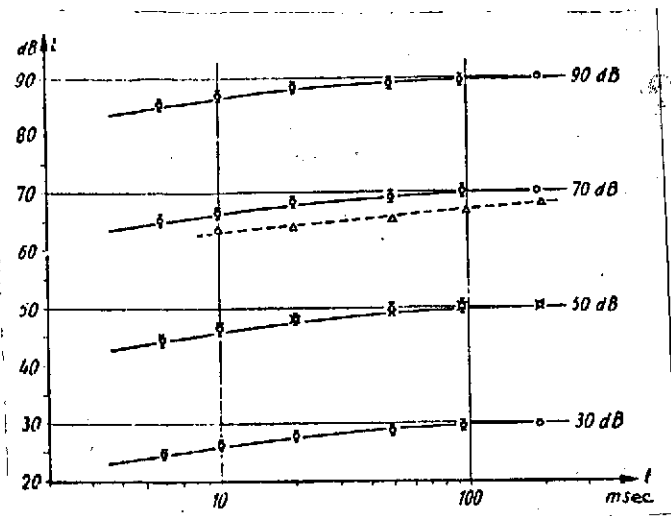
Fig. 5. Subjective loudness of short tones as function of duration with steady sound levels as parameter.

× Single-ear measurements
Δ Inertia of readings in accordance with proposals for psophometers [10]

mean value was computed as the arithmetic mean of the /148 linear acoustic pressure or voltage values. If we reflect on the nature of appropriate averaging in subjective loudness studies, we realize that it is the sound-level values which must be averaged to best approximate the laws of perception. However, if the judgements are very close together, the type of averaging plays virtually no role, so that we can dispense with the conversion in this case. For each point plotted, the standard deviation calculated from the sum of the squares of the deviations from the mean and the number of judgements is also entered. It can be seen from the diagram that there is no conspicuous change in the rise of the sound level between 30 and 90 dB for the steady tone. It can also be seen that the effective durations must be quite small before there is any detectable drop in loudness.

The points on the 50-dB curve also marked with a cross reproduce the single-ear measurements with 40 judgements per point. It can be seen from the positions of the points that the speed of the perception reaction is independent of whether one or both ears are used for listening.

At the 70-dB level, as a comparison, proposals for the DIN psophometer relative to dynamic indication sensitivity are plotted as triangles. The proposals establish the indicated decreases in

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the readings as the duration of a short-tone stimulus decreases.
The measurements furnished by the psophometer are intended more
for judging the annoyance caused by a noise. There is no definite
relationship between loudness and discomfort, but short sound
pulses appear to be more bothersome than their loudness would
indicate. Judging from the measurements we have obtained, this
proposal for the dynamic indication sensitivity of the noise meter
is not a fortunate one.

As for the design of objective loudness meters and psophometers,
the results of our measurements mean that for all sound signals
longer than about 50 msec, the inertial property must be gauged so
that the reading attains virtually the steady-tone value. For a
duration of 5 msec, however, the reading must be about 6 dB lower
than the full value. Hence, a pure peak-value meter would give
readings which were 6 dB too large for sound pulses lasting only
5 msec. No proposal at all is made for the dynamic indication
sensitivity of the DIN loudness meter in this range.

In order to see precisely whether there is any variation in
the loudness-rise law as sound level changes, the dimensionless
rise function $\phi(t)$ is plotted linearly in Fig. 6, independent of
sound level. As stated in the caption to the diagram, a special
symbol is used for each level. Including the spreads in judgement
values would clutter up the diagram too much, so they are omitted.
The measurements corresponding to the various levels show that
there is no hint of any dependence on level. Instead, the measured
points for the individual level values have irregular positions
from one time segment to the next, and their ranges of variation
overlap. Since no systematic change in the rise function can be
detected over a range of acoustic pressures covering three orders
of magnitude, even between the measurements for the greatest and
the smallest sound levels, it can be assumed that this function is
valid far above 90 dB and below 30 dB. It could be that there
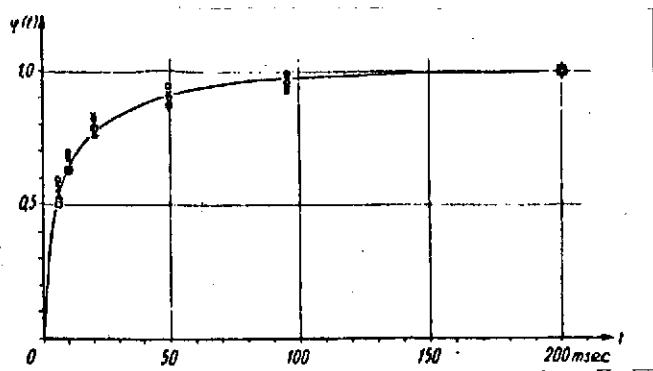would be some other type of inertial effect in the ear in the

Fig. 6. Dimensionless loudness rise
function φ(t) found from the measure-
ments. Measurements given for
various steady-tone sound levels.
O Sound level L = 90 dB
× " " L = 70 dB
⊡ " " ⌐L = 50 dB
Δ " " L = 30 dB
+ " " L = 50 dB (single-ear
measurement)

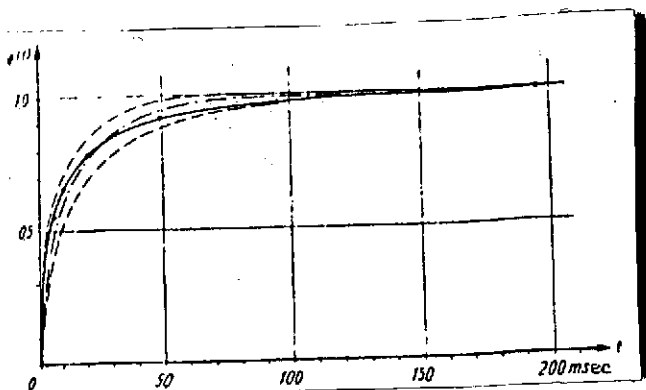Fig. 7. Loudness rise function φ(t)
as mean value from the judgements
at all measured loudness levels.

——Loudness rise function φ(t)
—·— Curve calculated with the
acoustic power time constant
τ₀ = 23 msec
——— Curves calculated with the
time constants τ₁ = 15 msec
and τ₂ = 30 msec

vicinity of the audi-
bility threshold or the
pain threshold. It is
nonetheless clear that
we only need to use a
single rise function for
loudness measurements
in the practical sound-
level range.

The irregularity
of the relative positions
of the points associated
with the various levels
and the overlapping of
the ranges of variation
justify taking a mean
value from all measure-
ments for each duration.
The rise function is then
obtained with great
accuracy, since each over-
all mean value represents
120 individual judgements.
Figure 7 shows a diagram
depicting the rise function
φ(t) as a solid curve with
the overall mean values.

If we wish to com- /149
pare this rise function
with the regularity
previously found by Niese
[5], in which the hearing

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organ is viewed as an energy storage unit with the time constant τ_O = 23 msec, the associated rise function produced by a sudden sound can be calculated from the differential equation

$$\tau_0 \frac{d\tilde{p}_D^2}{dt} = p^2(t) - \tilde{p}_D^2$$

in line with the energy storage concept. The differential equation describes an inertial system, where the input $p^2(t)$ is proportional to acoustic power and the output p_D^2 describes the loudness sensation expressed as the square of the [acoustic pressure of the] steady tone perceived to be equally loud. For a suddenly beginning sound, the differential equation and the boundary condition $p(t)$ = = $\tilde{p}$ at t = 0 supply the solution

$$\tilde{p}_D = \tilde{p} \left[1 - e^{-\frac{t}{\tau_0}} = \tilde{p} \cdot \varphi'(t) \right]$$

Substituting τ_O = 23 msec, and calculating the square root -- the rise function labeled $\phi'(t)$ -- the "dot-dash" curve in Fig. 7 is obtained. It does not agree absolutely with the measured rise function, but the approximation is good. Obviously, all the aspects of the inertial effect in the ear cannot be described by one simple exponential function. However, considering the ear as a simple inertial system satisfies many of the requirements. For instance, if the errors resulting from this model are estimated, the deviations turn out to be on the order of about 1 dB. Moreover, using the approximation $\phi'(t)$ produces small positive errors for durations over 25 msec, and small negative differences under 25 msec. This tendency can already be seen in the earlier measurements of Niese [5].

It is not surprising that the ear, with its completely different type of hearing mechanism relative to the inertia of loudness perception, obeys quite different laws than those reflected by a single time constant. Perhaps the inertial property of hearing is composed of various partial inertias. For instance, the potential

formation based on physical and chemical processes in response to stimulation of the acoustic nerves will require time; the propagation speed of the signals in the nerve pathways will also play a role; and finally, the production of the subjective impression in the central nervous system will be accompanied by inertial properties. Instead, it is surprising that an inertial model with a single time constant provides such a good approximation, so that it can be assumed that an inertial effect corresponding to energy storage plays the crucial role in the inertia of the hearing mechanism.

Trying time constants other than τ_o = 23 msec in an effort to better approximate the measured rise function shows that just changing it by ±30%, which corresponds to values of about τ_1 = 15 msec, and τ_2 = 30 msec, produces greater differences than the description with τ_o = 23 msec in the middle range of durations between 10 and 50 msec. The rise functions computed with τ_1 and τ_2 are shown in Fig. 7 as broken lines. They do not intersect the measured rise function, but rather lie completely above or below the curve to be approximated. Nevertheless, the curve with τ_2 = = 30 msec gives a somewhat better fit for durations above 50 msec, and the description with τ_1 = 15 msec is somewhat better below 10 msec.

However, for simulating the inertial property of hearing in objective loudness meters, using only one time constant τ_o = 23 msec appears most reasonable, both because of the small positive and negative errors and because of the simple, electrical principle involved in accomplishing it. As these studies show, the inertial property of hearing is independent of level over a wide range, and, as Niese [5] found from measurements with sinusoidal short tones of various frequencies, independent of frequency as well.

4. Application to Objective Loudness Meters

The rise process in loudness perception can be described in close approximation by considering the ear as a simple, closed inertial system with a time constant of $\tau_o = 23$ msec for acoustic power. Steudel [9] studied the subjective decay process when a tone is suddenly cut off and found that this process can be described with a time constant $\tau \approx 50$ msec for acoustic pressure, independently of frequency. Retaining the assumption of a simple inertial system, and studying the form of the decay process, the above differential equation with the boundary conditions $p(t) = 0$ and $\tilde{p}_D = \tilde{p}$ at $t = 0$ yields the solution:

$$\tilde{p}_D = \tilde{p}\sqrt{e^{-\frac{t}{\tau_o}}} = \tilde{p} \cdot e^{-\frac{t}{2\tau_o}}$$

Thus, for the acoustic pressure $\tilde{p}_D$ of the steady tone perceived as equally loud, we obtain an exponential drop with a time constant of $2\tau_o = 46$ msec. In view of the approximate agreement of this constant with the one measured by Steudel, it seems permissible to ascribe a certain general validity to the model represented by the differential equation.

On the basis of this model, Niese [6, 7] calculated the loudness of a number of well-defined acoustic processes with rather rapidly fluctuating time functions, and then determined the loudness from the judgements of a large number of subjects. Good agreement was obtained between computation and subjective measurement, as long as the maximum of the computed time function for loudness was taken as "loudness-determining." Encouraged by these results, Niese [4] developed a loudness meter, which electrically simulates this inertial property. In testing on 21 different practical noise forms, good agreement with subjective judgement was obtained.
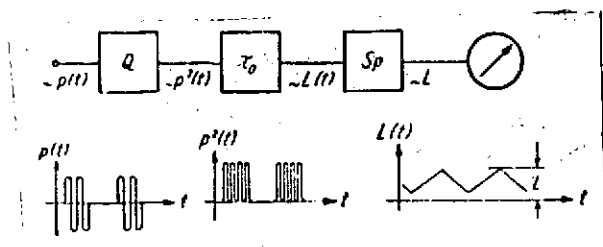
Fig. 8. Schematic of required
functions in an objective
loudness meter for correctly (with
respect to hearing) evaluating the
influence of time variation of
noises.

Loudness measurements
which agree well with sub-
jective judgements are
obtained when, in accordance
with the observed regularity,
the acoustic-pressure time
curve is converted to an
acoustic-power time curve,
and the latter travels
through an inertial system
with time constant τ_0 = 23 msec. Finally, the peak value of the
new time function resulting from the passage through the inertial
system must be determined, and its logarithm indicated by the meter.
Such a measuring system must therefore be designed as in Fig. 8.
The input, proportional to acoustic pressure, first travels through
a unit (Q) with a quadratic characteristic, so that its output is
a time curve proportional to acoustic power. The following time-
constant unit (τ_0) filters out the higher frequencies within the
envelope curve of the time function, and, depending on the rapidity
of the amplitude fluctuations, distorts the envelope curve so that
a new output is obtained which, based on the same charging and
discharge time constants, oscillates about the square of the
effective value. Next, a peak-value former (Sp) takes the peak
value of this new output, and a logarithmically calibrated
instrument gives the reading.

For example, the electrical measurement apparatus can be the
circuit in Fig. 9a. Here, with the aid of a transformer, the
measurement voltage proportional to acoustic pressure is fed to a
full-wave rectifier with a quadratic current-voltage characteristic.
The resulting voltage on the operating resistance R_a is proportional
to acoustic power, and is applied to the grid of an amplifier tube
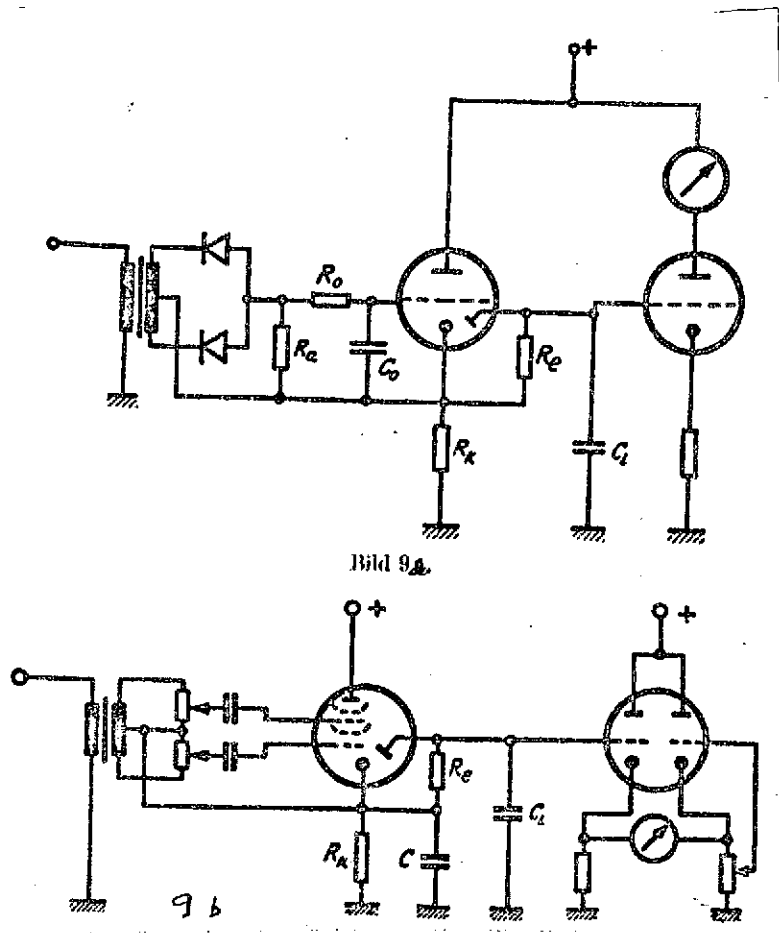through the time-constant unit $\tau_0 \approx R_0 \cdot C_0$. The amplified voltage

Bild 9a.

9 b

Fig. 9. Examples of electrical arrange-
ments corresponding to Fig. 8.

is produced across the cathode resistance R_k of this tube. In combination with the charging capacitor C_L and the discharge resistance R_e, a diode path in this tube system takes the peak value. In accordance with the mode of operation of this arrangement, the peak-value former has a small charging time constant $\tau_{ch} \approx R_k \cdot C_L$, which must be smaller than τ_0, and a large discharge time constant $\tau_{dis} \approx (R_k + R_e) \cdot C_L$. In the anode circuit of a subsequent tube, the peak value can then be displayed with the aid of an instrument, where a customary circuit arrangement can be attached for closed-circuit current compensation. The scale of the indicator instrument can either be logarithmically calibrated or, by suitable grinding of the pole shoes of the magnet in the indicator instrument, can be given a linear phon scale.

Figure 9b shows the principle of another circuit using a mixing hexode. The grids of the hexode system receive the input voltage in phase opposition. If the amplitude ratio of the supply voltages and the grid bias voltages is suitably chosen, the resulting voltage on the cathode resistance R_K is the square

of the input. The triode system is hooked up as a diode and takes the peak value. If $C_L \ll C$, the time constant $\tau_o \approx R_K \cdot C$ carries out the inertial weighting of the voltage proportional to acoustic power. C_L is included in the charging process through the open diode path and has the same voltage as the capacitor C. In the discharging process of the capacitor C, the diode cuts out the   capacitor C_L, so that the latter can only discharge through the resistance R_e with a large time constant. To measure the voltages on C_L, a triode is hooked up in a bridge circuit.

Compared to the circuit with dry-plate rectifiers (Fig. 9a), this circuit arrangement has the advantages that there is no temperature dependence and that the external resistance of the supply voltage source can be chosen arbitrarily large without worrying about characteristic curve shifts.

This arrangement is somewhat more elaborate than usual root-mean-square loudness level meters, but it provides compensating advantages in the selection of the quadratic rectification region. Practical noises can be very peaky, for example the noises of internal-combustion engines, compressed-air hammers, typewriters, automatic punches, etc. With such noise forms, there is often a difference of more than 20 dB between the peak value and the root-mean-square value. If the root-mean-square value of such noises is to be measured correctly, the peaks present must also be amplified and squared without distortion, i.e. the amplifier and the modulating capacity of the quadratic characteristic must be overdesigned by at least 20 dB. This is not a great technical problem for the alternating-current amplifier. However some difficulties do arise in the squaring required for generating the root-mean-square value. If, as is customary, an indication range of 12 dB is desired, a quadratic rectification relationship is required over a range of 32 dB in all. However, extreme efforts are required to design customary quadratic rectifiers for such a

large region. The resulting output voltages will be very small. They cannot directly modulate a measuring instrument, but must first be d.c. amplified.

This problem also applies to all root-mean-square vacuum-tube voltmeters, as long as very peaky voltages are used for the measurement. In using root-mean-square measuring devices, we must first ascertain the maximum peak/effective-value ratio at which such measuring devices are usable. As for loudness level meters, it appears that sometimes the manufacturers are not sufficiently informed about the existing requirements or, knowing the requirements, simply supply what they can based on economic considerations, without disclosing the limitations. The DIN provisions do not touch upon this problem.

As for the indicator circuit of loudness level meters, for "true-to-hearing" evaluation of the amplitude statistics of noises, the previously discussed proposal that, instead of the effective value, a specific value between this root-mean-square value and the peak value must be measured, considerably reduces the requirement relative to the reserve for the quadratic characteristic curve. Investigated on this basis, extremely peaky noise forms show that there will only be a difference of about 10 dB between the peak value and the correct loudness measurement to be indicated, so that, for full deflection of the indicator, the amplifier and the range of quadratic rectification have to be overdesigned by only 10 dB. Hence, with the indication range of 12 dB, squaring is only required over about 20 dB. Such a range can easily be achieved with customary quadratic units, and this increases the output voltage by a factor of 20.

5. Summary

The simulation of dynamic hearing properties is of interest in the development of objective loudness level meters and psophometers.

Recently, investigations on the inertial property of the ear have been published, viewing the ear as an inertial unit with a time constant of 23 msec for acoustic power. These studies were conducted at various frequencies and there was no evidence to indicate that the inertia of the ear was frequency-dependent. In making such proposals for simulating the dynamic hearing properties in objective loudness level meters the question arose of the level-dependence of the inertia of the ear.

The studies reported in this article should assist in clarifying this problem. In comparison with previous studies, a refined measuring technique was employed. In order to eliminate any measurement errors due to the different duration ratios of the short tones presented for measurement in subjective loudness comparisons, the duration ratios always had the value 1:2. Moreover, any possible influence on loudness perception due to the spectra of various widths resulting from the variable durations of the short tones was suppressed by an appropriately chosen band limitation. At the sound levels 30, 50, 70, and 90 dB, a loudness rise law as a function of tone duration was derived from the judgements on perceived loudness of the short tones. It was found that the rise laws obtained at different levels were identical, and thus the inertia of the ear was independent of level at least between the sound levels 30 and 90 dB. This observation justified developing a uniform loudness rise law from the entire collection of judgements with expectations of great accuracy. The discussion of the behavior of the curve showed that it was not purely exponential and thus could not be completely described with a single time constant. A single number can be used to describe the loudness rise law in good approximation when, as found earlier, the curve is compared with an exponential function with a time constant of 23 msec for acoustic power. If the loudness rise law is split into several subregions, better agreement is obtained for very short sound processes when a time constant of about 15 msec is employed. For relatively long-lasting sound processes, on

the other hand, the approximation with a time constant of 30 msec is more favorable.

For simple simulation of the dynamic hearing properties in loudness level meters and psophometers, the given mean time constant of 23 msec is recommended. Since the differences are positive and negative, it can be estimated that for practical noise forms, there will be only errors on the order of 1 dB. A comparison with the results of Steudel's measurements on the loudness decay process shows that considering the ear as an inertial closed system also correctly describes the decay process with the proposed time /152 constant. This observation permits a general formulation of the inertial property of the ear, which can be expressed by a differential equation.

To utilize electrically the inertial property described by the differential equation in the development of loudness level meters and noise meters, two circuits are proposed. The input proportional to acoustic pressure must be squared, and then passed through a RC unit with $\tau_0 = 23$ msec. The peak value of the resulting output is then indicated.

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